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Editorial

Special issue for Professor Roderick Melnik: Coupled complex systems and multiple scales, their modelling, and applications

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This special issue in the *Electronic Research Archive* journal is dedicated to Professor Roderick Melnik to celebrate his contributions to the field of coupled complex systems and multiscale modelling with their applications. Over the past two decades, Professor Melnik has been the Tier I CRC in Mathematical Modelling at Wilfrid Laurier University, based in Waterloo, Canada. He is also affiliated with the University of Waterloo and the Basque Centre for Applied Mathematics in the European Union. Currently, he serves perpetually as the Laurier Research Chair in Mathematical Modelling for Data-Driven Applications, AI, and Complex Systems. Throughout his career, he has received multiple prestigious awards in Canada, Spain, Italy, the United Kingdom, and Denmark.

Professor Melnik's early interest in complex systems was closely linked to applied mathematics and computational challenges in mechanical engineering, mechatronics, and materials science. He made significant contributions to the field of smart materials and structures, notably being the first to rigorously prove the well-posedness of a broad class of fully coupled electromechanical models in dynamic scenarios. During his time in Australia, Professor Melnik worked at the University of South Australia and the University of Southern Queensland before moving to the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Sydney. Throughout this period, he contributed to the development of reduced-order models for various classes of coupled complex systems described by strongly nonlinear time-dependent mathematical models. The methodologies and techniques he developed have proven essential for numerous data-driven applications and artificial intelligence (AI).

Today, reduced-order models and AI, particularly machine learning, are increasingly used together to create simplified and computationally efficient models of complex systems, enabling faster simulations and predictions.

Working with his students and collaborators, he pioneered computationally efficient low-dimensional reductions of coupled complex models, particularly in thermomechanical systems that exhibit dynamic phase transitions—such as those occurring in materials with memory. During this time, he made significant contributions to the fundamental problems at the intersection of control theory, information theory, and the evolution of dynamic systems. He introduced several foundational concepts and addressed various problems in industrial and applied mathematics, as well as numerical analysis. His work included topological analysis of eigenvalues in computational science and engineering. Much of his research involved modeling coupled complex systems using high-performance computing, particularly in the context of dynamic climate interactions, where he proposed innovative perspectives on these systems. Today, he continues to tackle a range of challenges in modeling for environmental sciences, including ecology. As the significance of coupled complex systems and networks grows increasingly important for the interconnected human-environment context, we anticipate that Prof. Melnik's research will continue to inspire future generations of researchers. Additionally, we would like to highlight his work on bio-inspired materials and complex biological systems, which he has pursued throughout his earlier career. His fascination with bionics and the mathematical applications in life sciences remains strong to this day.

After returning to Europe to take on his full professor position and lead the MCI group in mathematical modeling at the University of Southern Denmark, he developed a strong interest in advanced technologies, which led to significant contributions in nanoscience and nanotechnology. He and his team pioneered modern methods for key classes of low-dimensional nanostructures, such as quantum dots. Their systematic incorporation of coupled effects, like electromechanical interactions, into band-structure calculations enabled more accurate and computationally efficient predictions of the properties of these structures under various geometries and boundary conditions. This work has been crucial for further advancements in theory and applications in the field.

With his career move to North America nearly 25 years ago, starting with a full professorship in the USA and later moving to his Tier I CRC position in Canada, his interest in multiscale problems has expanded significantly, spanning from the nanoscale to planetary and global scales. At Laurier, he has taken on leading roles in mathematical modelling and interdisciplinary science, managing key initiatives such as the International AMMCS framework (Applied Mathematics, Modelling, and Computational Science) and the MS2Discovery Interdisciplinary Institute, of which he is the Founding Director. Throughout the years, his M3AI Research Group has been a driving force for new ideas that integrate mathematical, statistical, and computational approaches for modelling complex systems. The implications of his groundbreaking work extend well beyond applied and computational mathematics, impacting the natural sciences, engineering, humanities, social sciences, and their intersections in areas such as human factors, human-systems interactions, brain research, complex social cognitive systems, and neuroscience.

Reviewing his publication list highlights the extensive scope of his research interests and presents a significant challenge in summarizing his scientific contributions due to their depth and breadth. His numerous deep and influential contributions have achieved a revered status within their respective fields, serving as fundamental resources for countless researchers and students. The overarching theme of his major contributions centers on complex coupled systems. For the past four decades, Roderick

Melnik has profoundly influenced the study of these systems and has established significant connections between them and various interdisciplinary fields. His professional activities across three continents exemplify his unwavering commitment to the interdisciplinary scientific community, marked by remarkable professional achievements and contributions to a wide array of topics. This special issue is dedicated to Professor Melnik, celebrating his exceptional contributions to the field of coupled complex systems and their applications. Throughout his illustrious career, Professor Melnik has reached remarkable milestones, leaving an indelible mark on the scientific community, and continues to work tirelessly on new scientific challenges.

In what follows, we provide an overview of this special issue, featuring 14 papers, published by established researchers from around the world.

In the first paper by Hu et al., a coupled numerical framework was developed integrating discrete element and multibody dynamics for optimizing the design of a flexible boundary particle damping system on the exposed platform, which is an essential spacecraft structure that supports precision components such as pyrotechnic separation devices, connectors, four-way valves, and liquid floats. In the second paper, Zhou et al. simulated the complex nonlinear dynamics of bursting of thalamic neurons related to Parkinson's disease. Their findings enhance our understanding of inhibitory regulation mechanisms and propose a novel explanation for the origins of thalamic bursting in Parkinson's disease. The third paper by Yu et al. presented a data-driven optimal control method for reducing the libration angle oscillation of a sub-satellite deployment of tethered satellite systems. The study employed a dynamic modeling approach, formulating and transforming the motion equations of the tethered satellite system into a state-space form that included nonlinearities and disturbances. To address control optimization, a critic-actor neural network-based method was employed, supported by an unscented Kalman filter for noise reduction and accurate state estimation. In the fourth paper, Wang et al. presented a primal-dual algorithm for distributed interval optimization problems. Moreover, a novel criterion was introduced to ensure linear convergence to the Pareto solution of a distributed interval optimization problem without strong convexity. The effectiveness of the proposed algorithm was further validated through numerical simulations, which demonstrated its linear convergence behavior. Zhan and Song presented a mathematical framework to investigate the complex rhythm and synchronization of a half-center oscillator under electromagnetic induction. The reported results revealed that the mutual inhibition has a weaker effect on the discharge rhythm than self-inhibition, and that synchronous half-center oscillator states respond more robustly to electromagnetic induction. Guo et al. proposed a maximum likelihood estimation algorithm for finite impulse response systems with binary observations and data tampering attacks. The parameter estimation algorithms were proposed for both known and unknown attack strategies, with direct application in the security identification of cyber-physical systems. The convergence condition and proof of convergence for these algorithms were also reported in the study. Furthermore, in another paper, Guo et al. proposed mechanism- and data-driven algorithms for accounting and predicting electrical energy consumption in medium- and heavy-duty plate rolling processes. In this study, a time-slice-based rolling power consumption calculation algorithm is presented, employing a modular framework that partitions total consumption into independently calculated components to improve accuracy and adaptability. Additionally, hybrid models that integrate data-driven and mechanistic methods are being developed for predicting motor power consumption.

Hu et al. proposed a novel quasi-zero stiffness vibration isolator model utilizing shape-memory alloy springs. The numerical model was formulated using Landau theory and the Euler-Lagrange equations, where the model parameters were identified through tensile tests and a nonlinear least-squares optimization procedure. Finally, the experimental platform was constructed to evaluate the isolator's performance under low-frequency excitation, confirming strong agreement with theoretical predictions and demonstrating effective vibration isolation at frequencies above 0.5 Hz. Suganya et al. presented a nonlinear mathematical model incorporating a Caputo fractional derivative to analyze the transmission of COVID-19. The study included an analysis of the existence, uniqueness, and stability of the proposed model, demonstrating its robustness and applicability in analyzing and managing pandemic situations. Chen et al. developed a stochastic pertussis model with immunity and Markov switching to investigate the impact of environmental perturbations and state changes on pertussis. Several examples were also reported in this study to confirm the theoretical findings. Xu et al. proposed a novel privacy-preserving distributed optimization algorithm for directed networks via state decomposition and external input. Apart from providing proof of convergence, the study also conducted a numerical simulation to illustrate the effectiveness of the proposed method in addressing privacy concerns in distributed optimization problems on directed graphs. Li and Wang study report two differential privacy algorithms to protect against data tampering attacks in finite impulse response system identification under binary observations. Furthermore, the experimental evaluation reported in the study confirms the effectiveness of the proposed algorithm in preventing data tampering while preserving parameter estimation accuracy. The study by Mazouz et al. reports a dynamic design and optimization of a power system DC/DC converter. A peak current mode control strategy operating in continuous conduction mode was proposed to regulate the terminal voltage of a constant-power load driven by a double-inductance buck converter. Both simulation and experimental results validate the proposed approach, demonstrating excellent dynamic response and stable performance under substantial load fluctuations.

The review paper by Assem et al. provides a comprehensive examination of various characterizations of sandpile dynamics arising in the literature referred to as "Abelian sandpile models". This review discusses highlights of the diverse approaches and perspectives in the study of the sandpile model, as well as the sustained interest in the subject to the present day, and then rigorously establishes the sense in which they are commutative and associative as algebraic structures. While these properties are discussed in seminal works on the topic, their justifications are often implicit, with some transitions in presentation treated as self-evident. This review provides more rigorous proof, clarifying the distinctions and connections between different interpretations of the dynamics, namely, how configurations are combined or how state transformations are performed on the graph. For many related facts or properties, this paper provides alternative proof techniques. Furthermore, this paper examines the Krohn-Rhodes complexity of finite Abelian semigroups, linking the sandpile model to a broader framework for analyzing discrete event dynamical systems. These observations, along with the alternative, extended, and detailed perspective on the fundamental properties of the sandpile model, offer valuable insights into its theoretical understanding by mathematicians and physicists, as well as for further exploration of its computational and dynamical complexity. Finally, this review paper also outlines suggestions for how to further relate this expanded framework to handle current and future generalizations of non-Abelian sandpile models.

We anticipate that by bringing together contributions from expert scholars worldwide, this special issue will serve as a hub for innovative ideas and collaborative opportunities, ultimately fostering further breakthroughs in this interdisciplinary field of research. Professor Melnik has generously shared his knowledge, wisdom, and friendship with his students, postdocs, and team members, as well as with scientists around the globe. He is widely recognized among younger generations as a visionary mentor who exemplifies generosity and compassion. For many, his papers have become an endless source of inspiration and new ideas. He remains a powerful generator of scientific innovation, actively tackling a range of challenging problems. We hope to benefit from his inspirational ideas for many years to come.

In conclusion, we would like to express our gratitude to the outstanding team at AIMS, with whom we were honoured to collaborate on this project. It provided an excellent opportunity to celebrate the achievements of the distinguished mathematician and scientist, Prof. Roderick Melnik. The AIMS team has also provided incredible support for the AMMCS framework initiatives and the international conferences held in Waterloo, for which we are thankful. We believe that the thirteen research articles and one review paper included in this Special Issue offer valuable insights that will inspire new ideas and foster future advancements in the fields of coupled complex systems, multiscale modelling, and their applications. We extend our sincere appreciation to all contributing authors for their high-quality work and to the reviewers for their thoughtful and constructive feedback.